CP violation in the Higgs sector (and SUSY).

♢ CP mixing induced in the Higgs sector due to CP violation in soft SUSY breaking parameters and effect of the CP phases on rates.

♢ Plugging the 'hole' in $\tan\beta$–M_{H^+} plane at low neutral Higgs masses, ($\sim 10 - 50$)GeV through the charged Higgs decay at the LHC.

$\not{CP}$ and SUSY

CP violation in SUSY: Ugly Duckling to Swan !

Large # (44 to be precise) of phases of the SUSY parameters $e.g. \mu, A_f, M_i, i = 1, 3$ **can not** be rotated away by a simple redefinition of the fields.

Older days:

These generate unacceptably large electric dipole moments for fermions. Fine tune all the $\not{CP}$ phases in SUSY to zero.

Now:

Ibrahim et al 97,Brhlik et al 98,Bartl et al 99,Falk et al 98,99, Nath, Utpal Chattopadhyaya, D.P. Roy., Y. Farzan (06)

It is possible for some combination of phases to be O (1) and yet satisfy *all* the constraints on EDM's provided the first two generation of squarks are heavy.

Few more things about this $\not{CP}$:

1. BAU may be generated with $\not{CP}$ in SUSY with light stops.

2. The MSSM $\not{CP}$ phases induce CP mixing in the Higgs sector (which has no CP mixing at the tree level) of the MSSM through loop effects Pilaftsis 98,Choi et al 00, Carena et al 00

3. CP mixing in the Higgs sector, one way for $\not{CP}$ in SUSY to manifest itself: can affect production rates at LHC as well. Dedes et al 99,Choi et al 01

Phenomenology of $\not{C}\not{P}$ violating MSSM at colliders.

Which phases can be large?

- μ, A_f and any two of the three gaugino masses M_1, M_2, M_3.
- Phases in the sfermion sector can also be non-zero.

◇ What can the phases do?

Exhaustive discussion for the e^+e^- case for the $\tilde{\chi}^{\pm}, \tilde{\chi}_0$ and the sfermions, charged Higgses.

Choi et al 98,00,01,03,04,Kneur99, Barger 01, Bartl et al 02,03, Christova + Kraml 02, RG + Kraml + Gadosijk

Effect of SUSY $\not{CP}$ on Higgs phenomenology

MSSM $\not{CP}$ phases $\Rightarrow$ $\not{CP}$ in the Higgs sector:

CP conserving MSSM Three Neutral Higgses h,H CP-even; A CP-odd

CP violation : ϕ_1, ϕ_2, ϕ_3 no fixed CP property

$m_{\phi_1} < m_{\phi_2} < m_{\phi_3}$

Sum rules exist for $\phi_i f \bar{f}$, $\phi_i VV$

(A. Mendez and A. Pomarol, PLB **272** (1991) 313. J.Gunion, H. Haber and J. Wudka, PRD **43** (1991) B.Grzadkowski, J.Gunion and J. Kalinowski, PRD **60** (1999) 075011)

$$g^2_{\phi_i WW} + g^2_{\phi_j WW} + g^2_{\phi_k WW} = g^2 m^2_W, i \neq j \neq k$$

First proposed in a model independent way.

The h, H, A now all mix and share the couplings with vector boson pair VV. Will affect production rates.

Predictions in terms of SUSY $\not{CP}$ phases in the MSSM for this mixing.

A few details of the mixing.

General two-Higgs-doublet Model:

Two complex $Y = 1$, $SU(2)_L$ doublet scalar fields, Φ_1 and Φ_2

Most general Higgs potential is:

$$\begin{aligned} V &= {m_{11}}^2\Phi_1^\dagger\Phi_1 + {m_{22}}^2\Phi_2^\dagger\Phi_2 - [{m_{12}}^2\Phi_1^\dagger\Phi_2 + h.c.] \\ &+\frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+\left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \left[\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right]\Phi_1^\dagger\Phi_2 + h.c.\right\} \end{aligned}$$

$$\text{Unitarity} \Rightarrow V \in \Re \Rightarrow \left\{ \begin{array}{l} \{m_{11}, m_{22}, \lambda_{1-4}\} \in \Re \\ \{m_{12}, \lambda_{5-7}\} \in \mathcal{C} \end{array} \right.$$

Notice that with one Higgs doublet, we can have no CP violation.

MSSM:

Higgs potential as 2HDM above with

$$
\begin{array}{ll}
m_{11}^2 = -m_1^2 - |\mu|^2 & \lambda_1 = \lambda_2 = -(g^2 + g^{'2})/8 \\
m_{22}^2 = -m_2^2 - |\mu|^2 & \lambda_3 = -(g^2 - g^{'2})/4 \\
m_{12}^2 = \mu B & \lambda_4 = g^2/2 \\
 & \lambda_5 = \lambda_6 = \lambda_7 = 0
\end{array}
$$

Vacuum expectation values:

$$
\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} e^{i\xi} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}
$$

At tree-level:

Minimisation conditions $\Rightarrow \arg(m_{12}^2 e^{i\xi}) = 0$

Rotate phase away with an appropriate choice of Φ_2

$$\boxed{\Phi_2 \rightarrow e^{-i\xi}\Phi_2 \Rightarrow \arg(m_{12}) = 0}$$

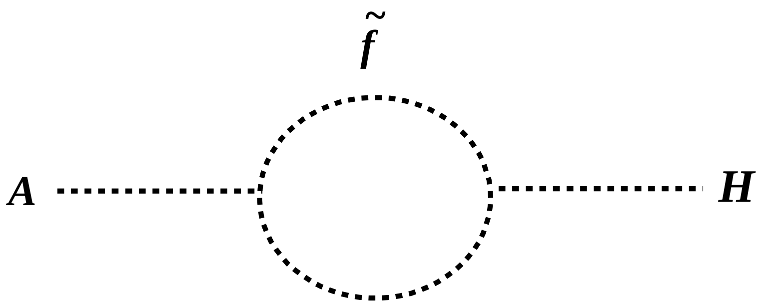
No CP-violation in tree-level Higgs sector

Higgs bosons are CP-eigenstates

At one-loop:

Now have $\arg(m_{12}^2 e^{i\xi}) \neq 0$

Potentially have CP-violation from soft-susy breaking terms $A_{t,b,\tau}$, M_3



$$\propto \frac{m_f^2}{m_{\tilde{f}_1}^2 - m_{\tilde{f}_2}^2} \Im m(A_f \mu)$$

write $A_f = |A_f| e^{i\Phi_{A_f}}$, $M_3 = |M_3| e^{i\Phi_3}$ and $\mu = |\mu| e^{i\Phi_\mu}$

CP-violation parameterised by $\{\Phi_{A_f}, \Phi_3, \Phi_\mu\}$

Higgs bosons are NOT CP-eigenstates

The CPX Scenario

[Carena, Ellis, Pilaftsis & Wagner, Phys. Lett. **B495** (2000) 155]

"designed to showcase the effects of CP violation in the MSSM"

$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = M_{\mathrm{SuSy}}$$

$$\mu = 4M_{\mathrm{SuSy}}, \quad |A_{t,b,\tau}| = 2M_{\mathrm{SuSy}}, \quad |M_3| = 1TeV$$

Allow the following parameters to vary:

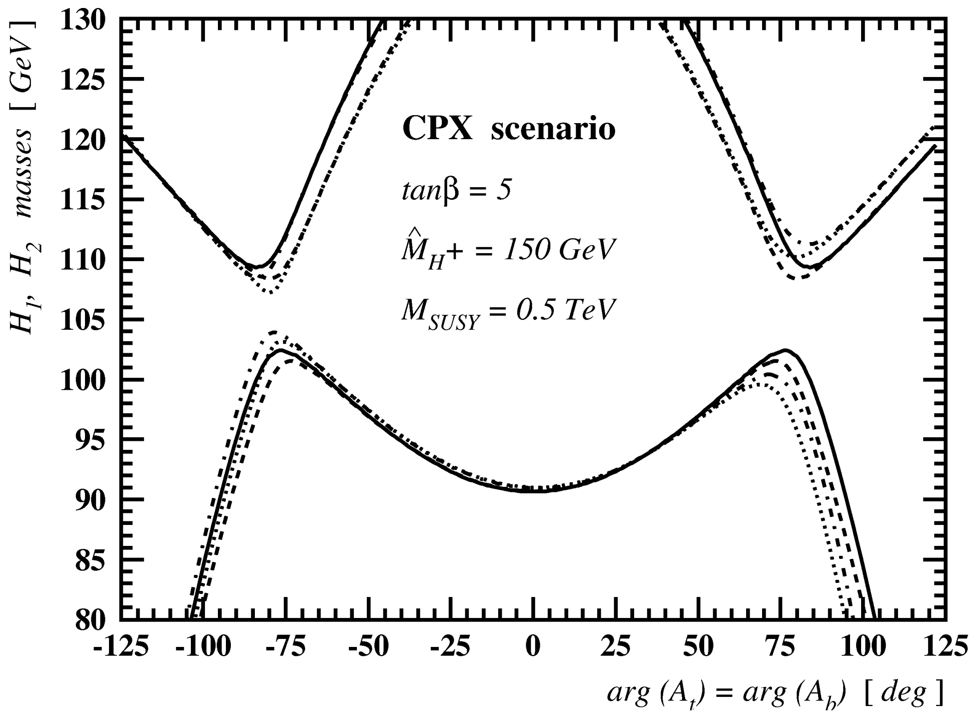
$$\boxed{\begin{array}{ccc} \tan\beta, & M_{H^\pm}, & M_{\mathrm{SuSy}}, \\ \{\Phi_{A_t}, \Phi_{A_b}, \Phi_{A_\tau}\}, & \Phi_3, & \Phi_\mu \end{array}}$$

Masses and couplings

[Carena, Ellis, Pilaftsis & Wagner, Nucl. Phys. B **625** (2002) 345]

CPX scenario with $\tan\beta = 5$, $M_{H^\pm} = 150\text{GeV}$, $M_{\text{SuSy}} = 500\text{GeV}$,
$\Phi_\mu = 0$, $\Phi_{\tilde{g}} = 0$ and $\pi/2$.

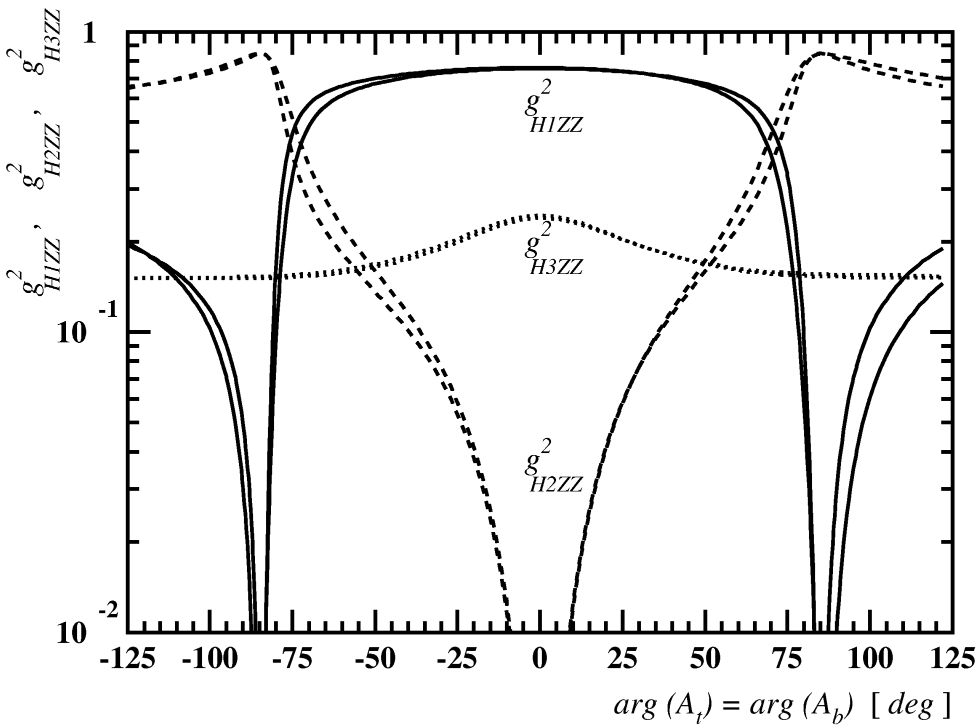
masses:



$M_{H_3} \sim 150$ GeV

$\Phi_{\tilde{g}}$ does not have
a big effect (two-loop)

couplings to VV:



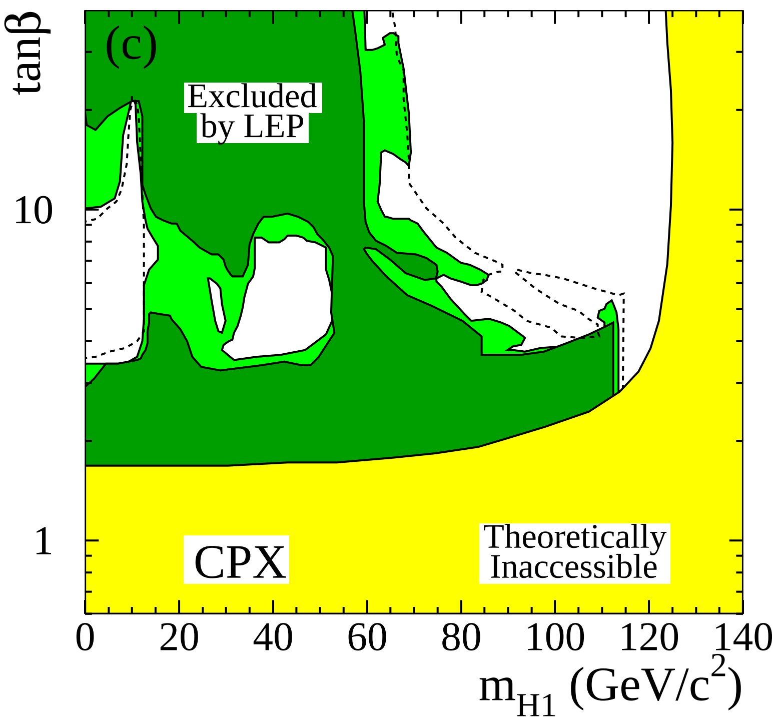
Sum rule for couplings

$$\boxed{\sum_{i=1}^{3} g^2_{\phi_i VV} = g^2_{\phi_i VV\,(SM)}}$$

Often $g_{\phi_i ZZ}$ vanishes!

$\Rightarrow$ light Higgs may have escaped LEP limits

LEP Limits Preliminary OPAL results :hep-ex/0406057, EPJC 37, 2004,49; LHWG-Note 2004-01,EPJC 47, 2006, 547



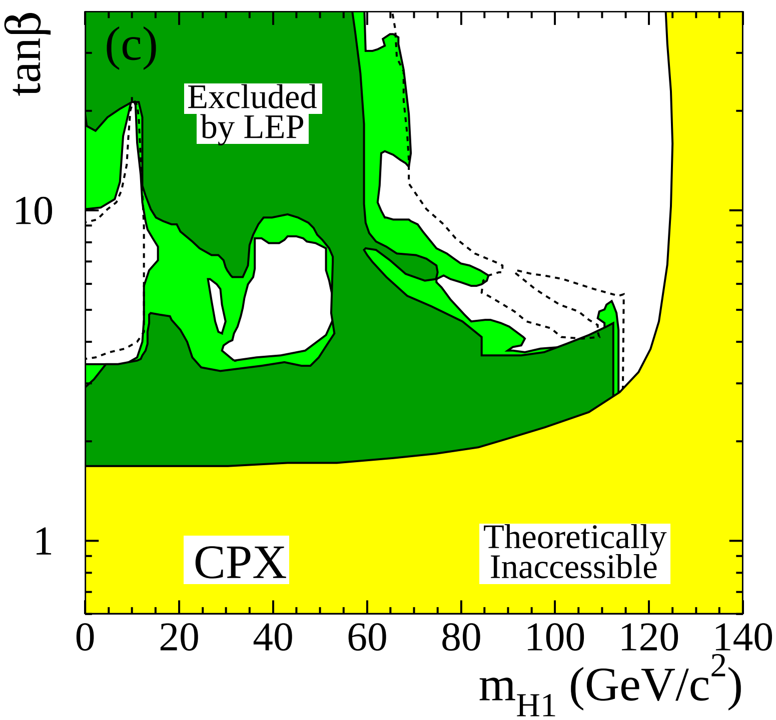
$$\Phi_{A_t} = \Phi_{A_b} = \Phi_{A_\tau} = \Phi_{\tilde{g}} = \frac{\pi}{2}$$

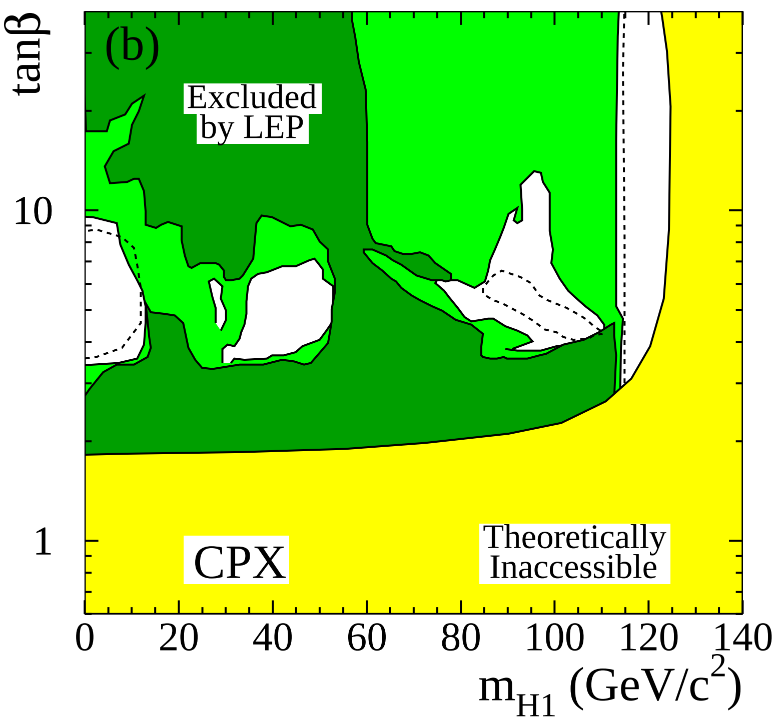
$$\Phi_\mu = 0$$

$$M_{\mathsf{SuSy}} = 500 \text{ GeV}$$

Even have gaps at 0–50 GeV!

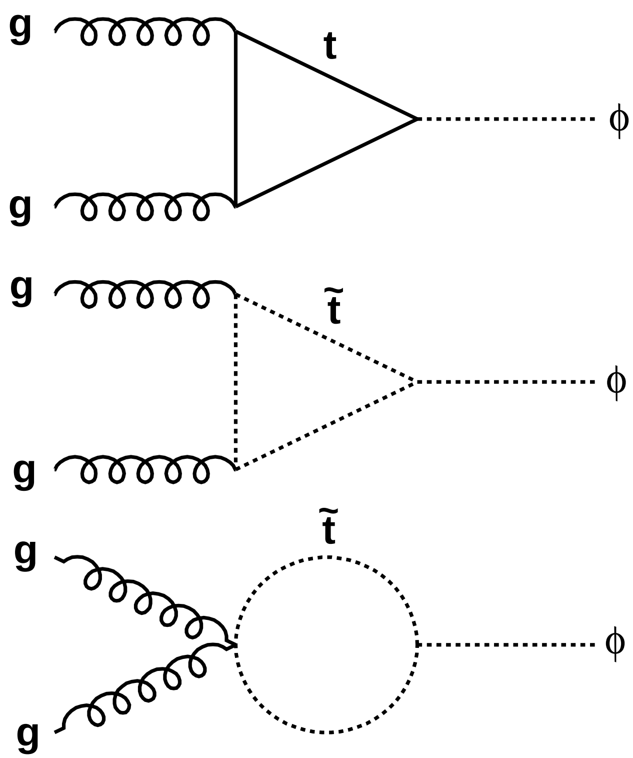
LEP Limits Depend on the program used for calculating CP mixing in the Higgs sector, top mass.





$gg \to \phi$ cross-sections

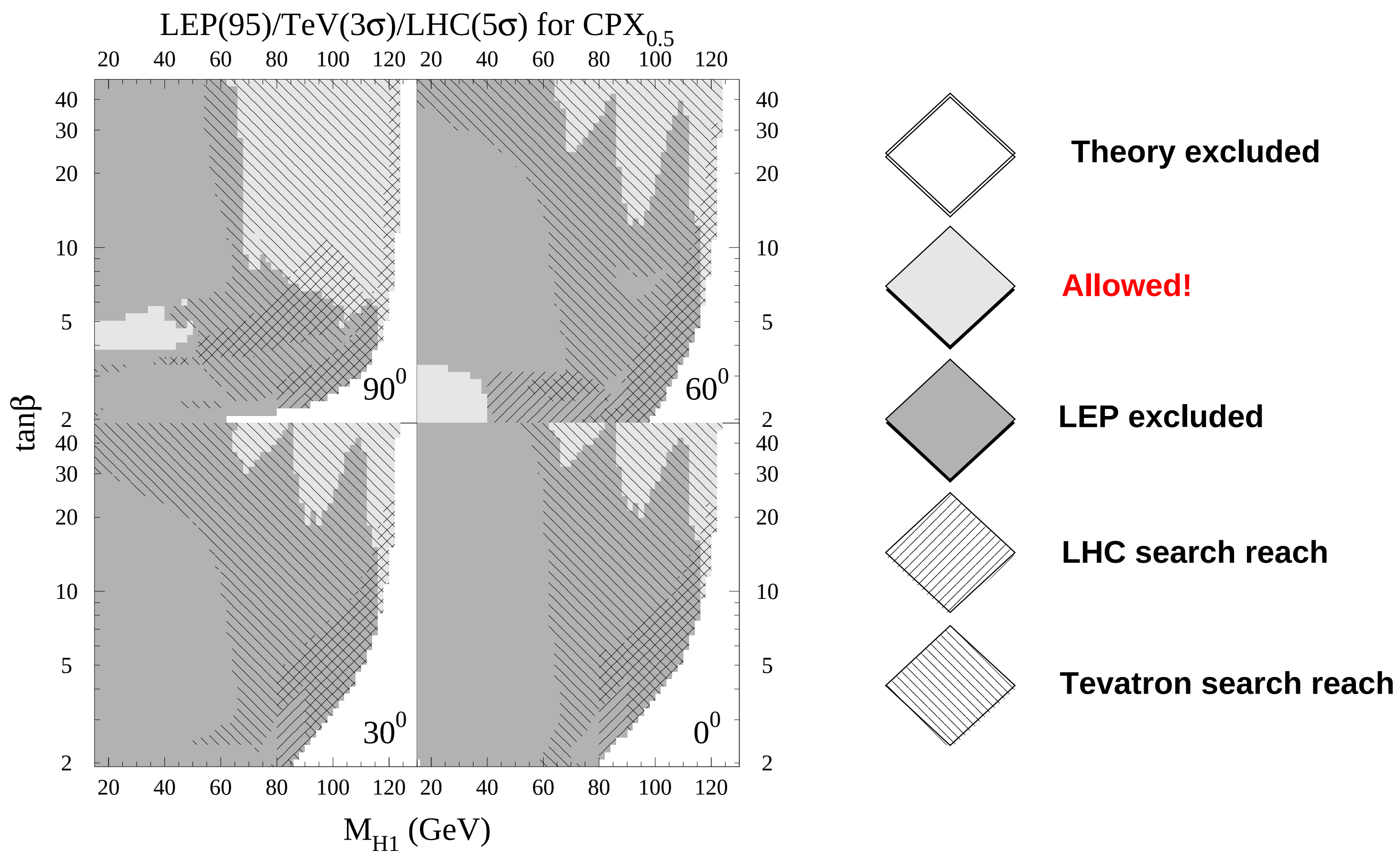
[Dedes, Moretti, Nucl. Phys. B **576** (2000) 29
Lee, Pilaftsis, Carena, Choi, Drees, Ellis & Wagner, Comput. Phys. Commun. **156** (2004) 283]



$$g_{h\tilde{t}_L\tilde{t}_R^*} = \frac{igm_t}{2M_W \sin\beta}(\mu^* \sin\alpha - A_t \cos\alpha)$$

$gg \to \phi$ cross-sections may be altered

[Carena, Ellis, Mrenna, Pilaftsis & Wagner, Nucl. Phys. B **659** (2003) 145]



Gaps in coverage! Need to look at the light higgs searches again.

A few observations

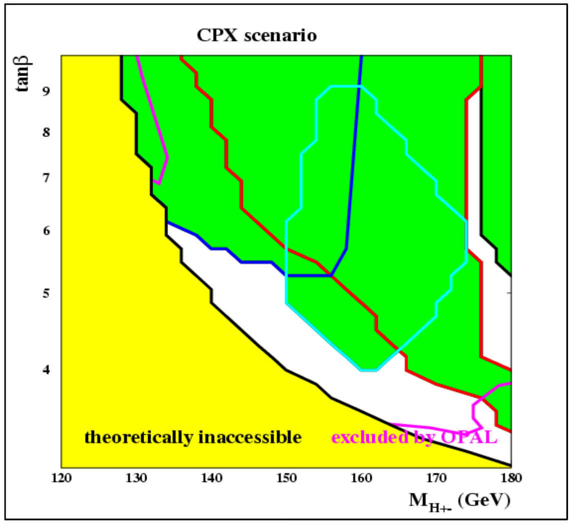
- Small regions in $\tan\beta, M_{H^+}$ plane where LHC,TEVATRON will have no reach

- Caused by reduced ϕ_1 coupling to W/Z AND *top*.

The higgs searches in $\not{CP}$ scenario need to be looked at carefully.

- **Usually this region has a light $H^{\pm}$. IS THIS ALLOWED BY, for example, $b \longrightarrow s\gamma$?**

What happens to discovery reaches our LHC friends present?



preliminary results presented by M. Schumacher at the meeting on 'CP violation and nonstandard Higgs' //http://kraml.home.cern.ch/kraml/CPstudies/

Published in CPNSH report.

A hole in the $\tan\beta - M_{H^+}$ plane: for $m_{\phi_1} < 50, 100 < m_{\phi_2} < 110$ and $130 < m_{\phi_3} < 180$.

The results of theory analysis verified.

Suggestion to fill the hole via h^+ decays

D. Ghosh, R.G. and D.P. Roy, Phys. Lett. B: 658

Observation:

There exists a sum rule for the couplings.

$$g^2_{\phi_i VV} + |g_{\phi_i H^+ W}|^2 = 1.$$

Since the couplings of ϕ_1 with VV,gg,$t\bar{t}$ are suppressed, ϕ_1 coupling to H^+W is large.

More important in this scenario the H^+ is light too.

In the 'window' where higgs signal might have been lost at LEP: Look for ϕ_1 production in H^+ decay, which in turn is produced in t decay.

(actually this would be true even in noncp violating supersymmetric scenarios as well if a non-chiral higgs singlet is present: D.P., P.N. Pandita, Sudhir Vempati; D.P. Roy, R.G.)

Small $\tan\beta$, light $M_{H^+} \Rightarrow$ large $B.R.(H^+ \to \phi_1 W)$.

Small $\tan\beta$, light $H^\pm$, ($M_{H^+} < M_t$) $\Rightarrow$ $H^\pm$ can be produced in the top decay

The sum rules on couplings means large $H^\pm W \phi_1$ coupling $\Rightarrow$ large $B.R.(H^+ \to \phi_1 W)$

$\Phi_{\text{CP}} = 90^\circ$.

$\tan\beta$	3.6	4	5
Br($H^+ \to \phi_1 W^+$)(%) Br($t \to bH^+$)(%) M_{H^+} (GeV) M_{ϕ_1} (GeV)	$> 90(87.45)$ ~ 0.7 < 148.5 (149.9) < 60.62 (63.56)	$> 90(57.65)$ $.7 - 1.1$ < 139 (145.8) < 49.51 (65.4)	$> 90(46.57)$ $1.0 - 1.3$ $< 126.2(134)$ $< 29.78(53.49)$

The BR ($H^\pm \to \phi_1 W > 47\%$ over the *entire* kinematic region in the light ϕ_1 window still allowed by LEP. The BR of $H^\pm$ in the usual $\tau\nu_\tau$ channel discovery discussed at LHC for the charged higgs suppressed by over an order of magnitude.

In the light ϕ_1 LEP window the $H^\pm$ can also be NOT searched for using the usual strategies for $\not{C}\!\not{P}$ case.

Look at

$$
\begin{array}{llllll}
pp \to t & & + & \bar{t} & + & X \\
\quad \hookrightarrow b\,H^+ & & & \quad \hookrightarrow \bar{b}\,W & & \\
\qquad \hookrightarrow W & H_1 & & \qquad \hookrightarrow q\bar{q}(\ell\nu) & & \\
\qquad\quad \hookrightarrow \ell\nu(q\bar{q}) & \hookrightarrow b\bar{b} & & & &
\end{array}
$$

Process allows a probe of a light $H^\pm$ **and** light neutral Higgs.

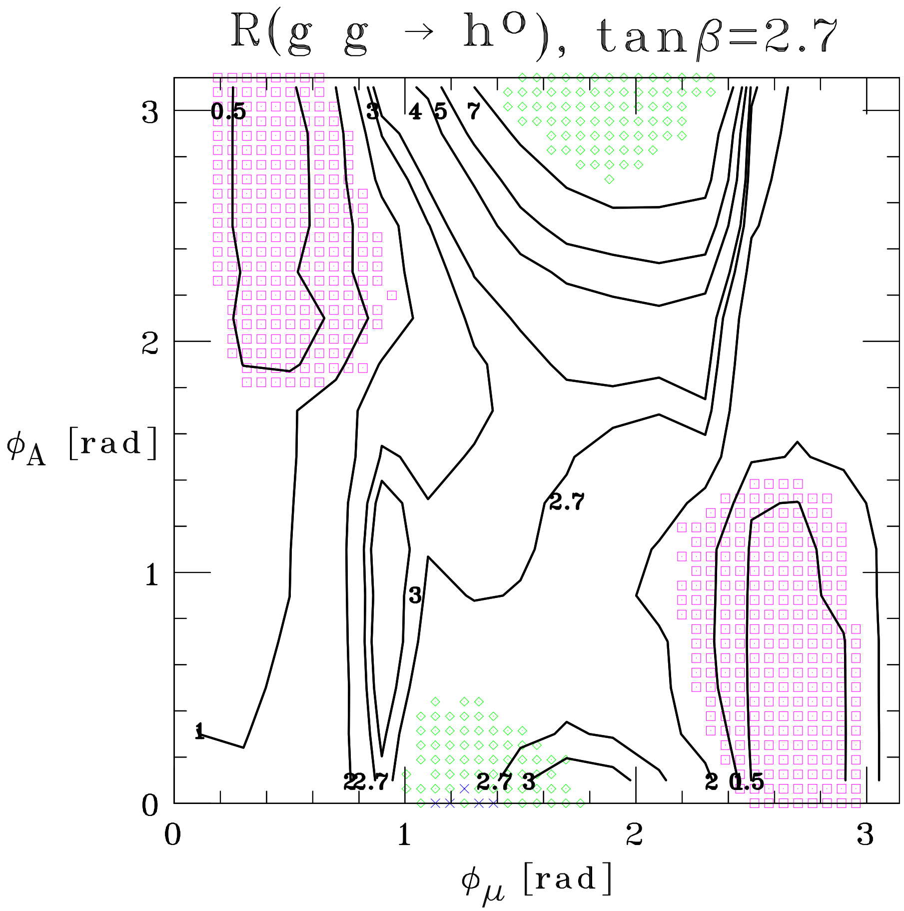
Use $t\bar{t}$ production with :

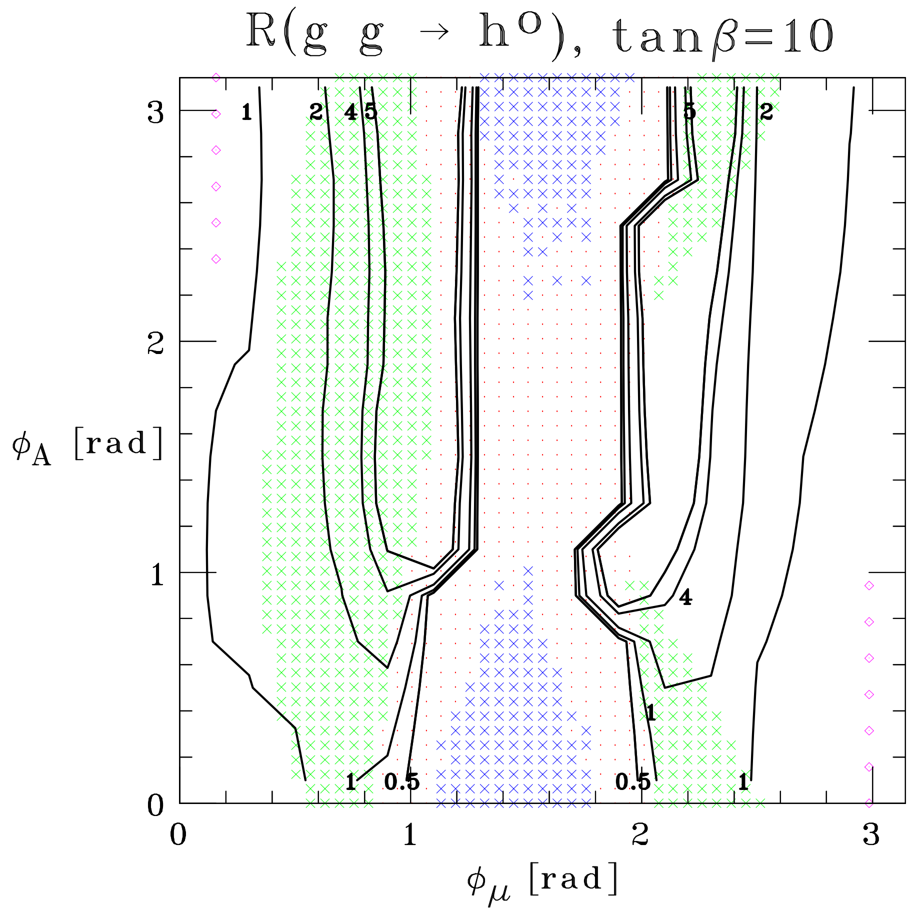
$t \to bH^+ \to b\phi_1 W \to bb\bar{b}W$ and $\bar{t} \to \bar{b}W$, with one W decaying leptonically the other hadronically. Hence both $W's$ can be reconstructed.

Look at the $WWbbbb$ events, demand three tagged $b's$.

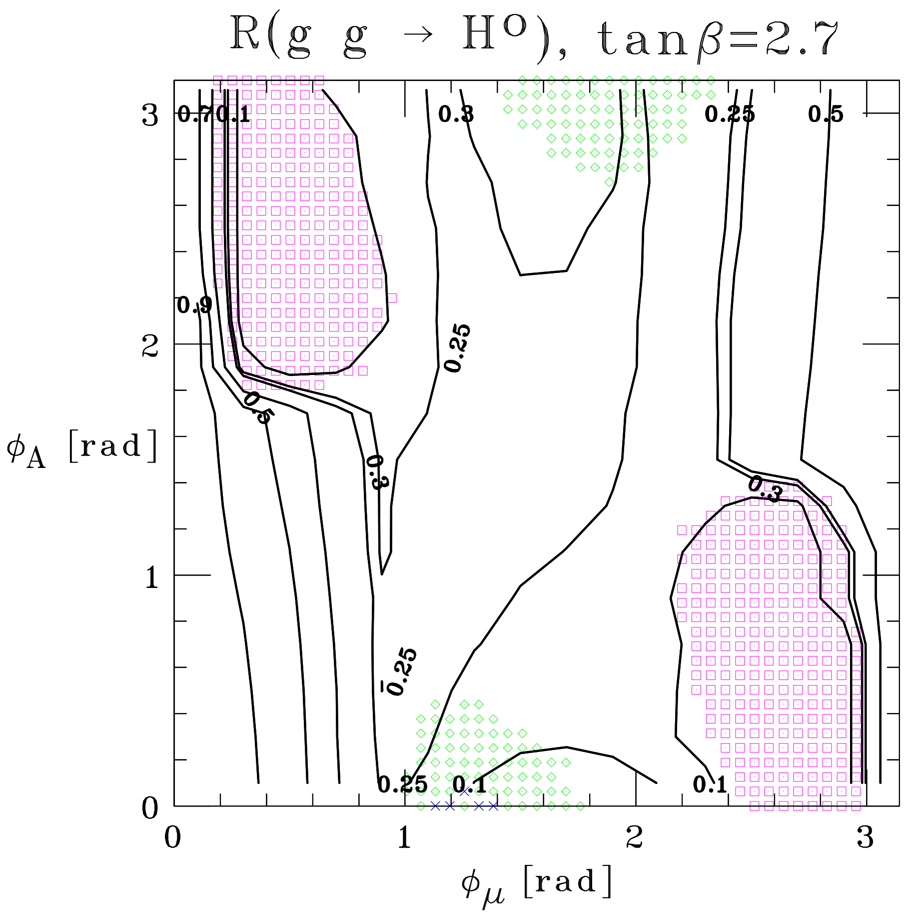
The mass of the $b\bar{b}$ pair with the smallest value will cluster around m_{ϕ_1} and $b\bar{b}W$ around M_{H^+}.

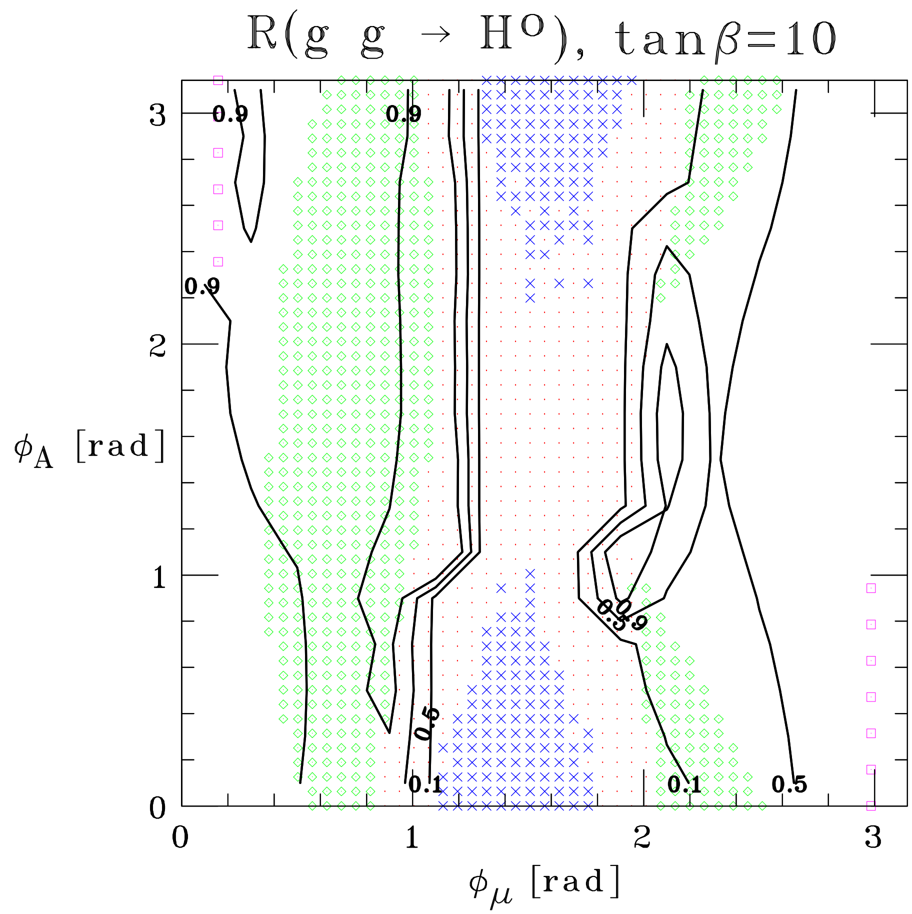
Effects of phases on rates even when Higgses are CP eigenstates.





Fortunately, $gg \to h$ only <u>increases</u> in allowed regions





$gg \to H$ decreases (as expected from coupling sum rules)

Electric Dipole Moments

[Dedes, Moretti, Nucl. Phys. B **576** (2000) 29]

Φ_μ and Φ_{A_f} are constrained by experimental limits of the EDMs of electron and neutron:

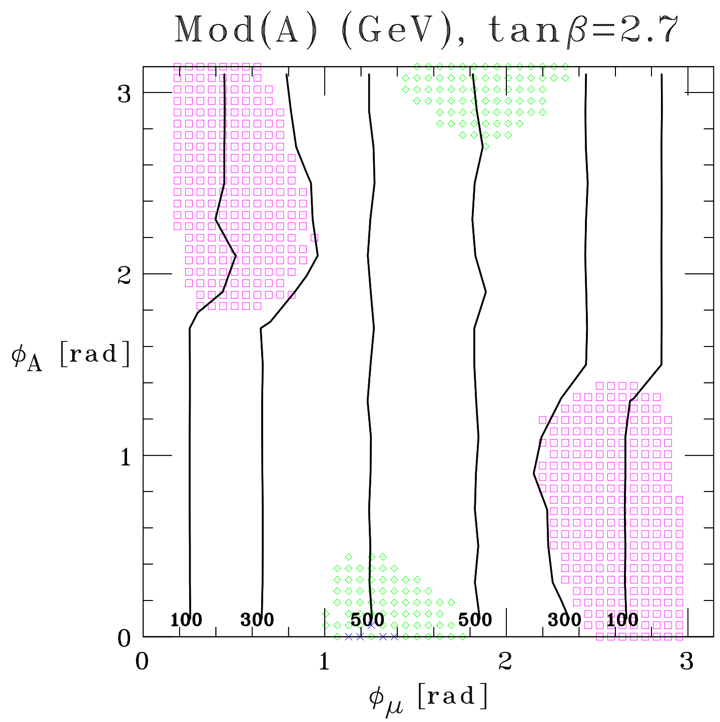
$$|d_e|_{\text{exp}} \leq 4.3 \times 10^{-27} e\,\text{cm} \qquad |d_n|_{\text{exp}} \leq 6.3 \times 10^{-26} e\,\text{cm}$$

e.g. at leading order:

$$\begin{aligned} \tan\beta &= 2.7 \\ |\mu| &= 600\text{GeV} \\ M_{\tilde{q}_{1,2}} &= 1000\text{GeV} \\ M_{\tilde{q}_3} &= 300\text{GeV} \\ M_{\tilde{g}} &= 300\text{GeV} \\ M_A &= 200\text{GeV} \end{aligned}$$

shaded areas excluded

Require $|A| >$ contour

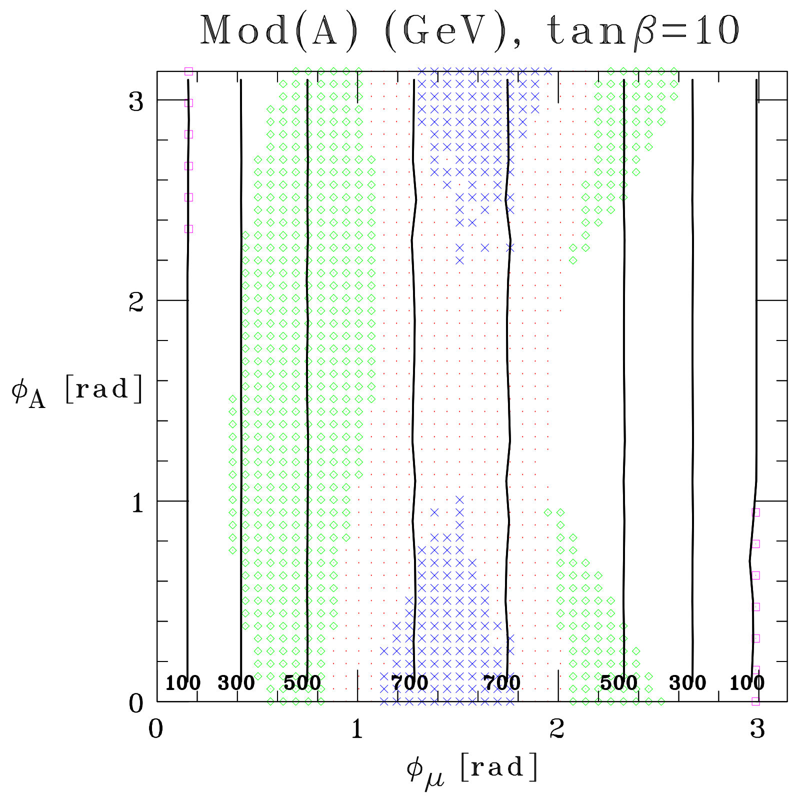


Higher $\tan\beta$ more difficult

$$\begin{aligned} \tan\beta &= 10 \\ |\mu| &= 600\text{GeV} \\ M_{\tilde{q}_{1,2}} &= 300\text{GeV} \\ M_{\tilde{q}_3} &= 300\text{GeV} \\ M_{\tilde{g}} &= 300\text{GeV} \\ M_A &= 200\text{GeV} \end{aligned}$$

shaded areas excluded

Require $|A| >$ contour



Much of the allowed region depends on accidental SuSy cancellations (fine tuning?)